



## Secondary metabolites synthesized by *Stemphylium lycopersici* and *Fulvia fulva*, necrotrophic and biotrophic fungi pathogen of tomato plants

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### ABSTRACT

The aim of this work was to study the volatile organic compounds (VOCs) profile and diffusible secondary metabolites (SMs) of *Stemphylium lycopersici* and *Fulvia fulva*, two fungal pathogens of tomato. *S. lycopersici* synthesizes and releases quantitatively more VOCs than *F. fulva*, probably due to the different type of interaction that each fungus establishes with tomato; nevertheless, *F. fulva* synthesized a specific and more diverse spectrum of VOCs. *S. lycopersici* released VOCs that triggering cell death in tomato leaves. Also, *F. fulva* synthesized an ample array of SMs but their biological roles remain to be elucidated.

### 1. Introduction

Tomato is one of the most consumed vegetable in the world [1], according to the Food and Agriculture Organization (FAO), approximately 60 million hectares produce 170.8 million tons [2]. In Argentina, the main areas cultivated with tomatoes are located in the provinces of Corrientes and Buenos Aires. In the latter one, production is carried out mostly in greenhouses [3], where relative humidity as well as temperature are high, favouring this the development of diseases provoked mostly by fungi [4].

Dothideomycetes is a class of fungi of the phylum Ascomycota that includes more than 25 orders of organisms adapted to a wide range of environments [5]. Among them, representatives of the genus *Stemphylium*, of the order Pleosporales, can establish pathogenic, saprotrophic, or endophytic relationship with a wide range of plant-host species [4,6]. *Fulvia fulva* (syn. *Cladosporium fulvum*) is also a dematiaceous

fungus, but in the order Capnodiales, that has been considered a model for the study of plant-pathogen interactions since it behaves according to the gene for gene hypothesis [7,8].

Based on their life cycle, fungal plant pathogens can be classified as biotrophic, hemibiotrophic or necrotrophic [9,10]. *Stemphylium lycopersici* is the causal agent of grey leaf spot, which is a serious disease of tomato in Argentina [6]. *F. fulva* is the causal agent of leaf mould, a disease that affects mostly greenhouse grown tomatoes [11]. Both are foliar diseases that provoke reductions in plants leaf areas and, therefore, in yield. While *S. lycopersici* is a necrotrophic pathogen [12], *F. fulva* is a non-obligate biotrophic one [13].

*S. lycopersici* might provoke plant cell death through the synthesis and release of phytotoxic secondary metabolites [14,10]. Interestingly, the chemical structure, as well as the biological effects of these molecules have been elucidated only for few of them [15–17]. The other fungus, *F. fulva* secretes into the apoplast a set of effectors [18], such as

**Abbreviations:** AVR, avirulence; ECP, extracellular proteins; FEEMs, fluorescence–excitation–emission matrices; FAO, Food and Agriculture Organization; KI, Kovalts Index; PDA, potato dextrose agar; PDB, potato dextrose broth; ROS, resistance oxidative stress; SMs, secondary metabolites; SAR, systemic acquired resistance; SIR, systemic induced resistance; VOCs, volatile organic compounds

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avirulence AVR2 [19], AVR4 [20], AVR4E, AVR9 [21], and AVR5 [22], and extracellular ECP1, ECP2, ECP4 and ECP5 proteins [23]. Recently, new secondary metabolites synthesized by *F. fulva* like cladofulvin [24] and 1,8-dihydroxynaphthalene-melanin [25,26] have been described.

Fungal secondary metabolites (SMs) are a wide range of low molecular weight organic compounds that are dispensable when microorganisms are cultivated *in vitro* but they provide adaptive advantages in nature. SMs might play relevant biological activities, that might affect food safety since some of them might be aflatoxins and/or trichothecenes or they might be useful of the pharmaceutical industry, since some SMs are key factors of pathogenicity [18]. It would be interesting to know whether their synthesis and/or secretion results in a compatible or incompatible interaction. Genes that code for the synthesis of SMs are arranged in clusters [27] and based on their biosynthetic pathway they might be classified as polyketides, non-ribosomal peptides, hybrid polyketide synthase/non-ribosomal peptide synthetase, terpenes or alkaloids [28]. According to their physicochemical nature, they can be volatile, soluble or insoluble compounds. Volatile ones might play an important role in long-distance biological interactions [29]. Several researchers found that many plants respond to a specific set of pathogen-derived volatile organic compounds (VOCs), which trigger direct and/or indirect defence responses [30,31]. Moreover, differential responses have been found regarding the nature of the plant stress, for example when the plant is attacked by a necrotrophic fungal pathogen, systemic induced resistance (SIR) might be triggered, while the systemic acquired resistance (SAR) is triggered by an environmental stress or a biotrophic fungi [32–35]. The information regarding the synthesis and/or secretion of VOCs by *S. lycopersici* and *F. fulva* and their role in plant pathogen interactions is lacking, therefore, the aim of this work was to analyse the profile of VOCs synthesized and released by a necrotrophic and a non-obligate biotrophic fungus that provoke diseases on tomato leaves as well as the soluble SMs that alter the plant physiology.

## 2. Materials and methods

### 2.1. Fungal material

The isolates of *Stemphylium lycopersici* (CIDEFI 213 and CIDEFI 216) and *Fulvia fulva* race-2 (CIDEFI 300) used in this work belong to the culture collection of the Centro de Investigaciones de Fitopatología (CIDEFI), Universidad Nacional de La Plata (UNLP) that have already been characterized [3,26,6]. The strains of *S. lycopersici* differ in their virulence.

### 2.2. Growth conditions

Fungal cultures of *S. lycopersici* CIDEFI 213 and 216 [6] were grown on potato dextrose agar (PDA) medium at 24 °C in the darkness for 7 days and *F. fulva* CIDEFI 300 under the same conditions for 14 days respectively [3]. Two agar plugs (diameter, 5 mm) from actively growing cultures were picked with a sterile glass borer and placed in a glass headspace vial (10 mL) filled with 3.5 mL of potato dextrose broth (PDB) medium (Sigma-Aldrich, Australia), which was sealed with a silicone septum cap. Vials were incubated in a rotary shaker at 150 rev. min<sup>-1</sup> at 24 °C in the dark for 7 in the case of *S. lycopersici* and 14 days in the case of *F. fulva*.

### 2.3. Volatile organic compounds (VOCs): extraction, identification and quantification

The VOCs profiles of fungi were analysed by gas chromatography–mass spectrometry (GC–MS) using a HP CGC 6890/MS Agilent 5975C VL gas chromatograph - mass spectrometer equipped with a ZB-5HT Inferno fused silica capillary column (30 m, 0.25 mm i.d., 0.25 µm, Phenomenex, Inc). A solid-phase microextraction fiber coated with

65 µm polydimethylsiloxane/divinylbenzene was used to extract VOCs from the stand still vials, that were incubated for an hour at 30 °C. After injection, the compounds were desorbed for 5 min in a splitless injector at 250 °C. The oven temperature was held at 40 °C for 2 min, then raised to 200 °C at 10 °C min<sup>-1</sup> and 250 °C at 15 min<sup>-1</sup>, then the temperature was hold for 5 min. Helium was the carrier gas flowing at 1 mL min<sup>-1</sup>. Compounds were identified by matching their mass spectra using the NIST Mass Spectra Search Program with NIST05 and Adams (Identification of Essential Oil components by Gas chromatography/Mass spectrometry, 4th Edition) libraries and using Kovalts index (KI) in reference to n-alkanes. The background of PDB media un-inoculated was analysed as control.

### 2.4. Spectrofluorometric supernatants of fungal cultures

An aliquot of the supernatants of fungal cultures grown on PDB were filtered through a 0.45 µm (pore) membrane to perform the spectrofluorometric analysis. The absorption spectra were measured on a Shimadzu UV-1800 at room temperature in quartz cells with 1.0 cm optical path length between 200 and 800 nm. The fluorescence–excitation–emission matrices (FEEMs) were determined using a Single-Photon Counting equipment FL3 TCSPC-SP (Horiba Jobin Yvon). FEEMs were generated by collecting the data of successive emission spectra according to described by Medina et al. [36].

### 2.5. Virulence assay

An aliquot of supernatants of fungal cultures grown on PDB were sterilized by passing the culture supernatant through a sterile 0.22 µm membrane. Virulence assays on detached leaves were carried out using unfiltered and filtered fungal culture supernatants as described [6]. As negative control leaflets were treated with an aliquot of sterilized water and un-inoculated PDB. The positive control was an unfiltered supernatant of fungal cultures grown on PDB for 7 and 14 days according the fungal specie (See section 2.2). Petri dishes were sealed with Parafilm and were incubated for a week at 25 °C. The average of the lesion was determined after 7 days post inoculation and was measured by means of the image analysis software Assess 2.0 [37]. The experiment was carried out with nine replicates of one leaflet per replicate inoculated with each strain. Data were analysed by analysis of variance (ANOVA) after the Tuckey test ( $p < 0.05$ ), with InfoStat version 2015 I [38].

## 3. Results and discussion

### 3.1. VOCs released by *Stemphylium lycopersici* and *Fulvia fulva*

Tomato is affected both by necrotrophic as well as biotrophic fungal pathogens that synthesize soluble and volatile secondary metabolites that alter plant physiology. The VOCs synthesized by *S. lycopersici* CIDEFI 213, CIDEFI 216 and *F. fulva* CIDEFI 300 are shown in Additional Figs. 1–3. The integrated areas were  $1.13 \times 10^8$  and  $6.18 \times 10^7$  for *S. lycopersici* strains CIDEFI 213 and CIDEFI 216, respectively and  $1.72 \times 10^7$  for *F. fulva* CIDEFI 300. These results showed that *S. lycopersici* produces a larger quantity of VOCs than *F. fulva*, which might be associated with their necrotrophic and non-obligate biotrophic nature, respectively [18,6].

Both isolates of *S. lycopersici* and the only one strain CIDEFI 300 of *F. fulva* produced a total of 25 volatile compounds (Table 1 and Table 2). It has already been demonstrated that *Stemphylium* species synthesize a wide array of SMs that might play, either alone or in mass, a key role during host plant infection [39] and also might explain their necrotrophic behaviour. Interestingly, among cultures of *F. fulva* the only SMs so far identified were cladofulvin [40] and 1,8-dihydroxynaphthalene-melanin [25,26]. However, our chromatographic analysis showed that *F. fulva* CIDEFI 300 synthesized 18 other SMs (Table 1). In line with this finding, Collemare et al. [18] reported that the genome of

**Table 1**

Relative abundance [%] of volatile organic compounds (VOCs) identified by means of a GC–MS analysis in cultures of *S. lycopersici* CIDEFI 213 and CIDEFI 216 strains grown in PDB media. Compounds presented in bold letters also were detected in cultures of *F. fulva* strain CIDEFI 300.

RT (min)	KI	Compound	CIDEFI 213	CIDEFI 216
1.64	624.27	Ethyl alcohol	14.12	21.08
1.74	629.54	<b>Acetone</b>	0.34	–
2.45	669.56	2-Methyl-1-propanol	4.94	6.81
3.72	740.64	<b>Isoamyl alcohol</b>	40.08	14.64
3.78	743.89	2-Methyl-1-butanol	25.45	41.46
5.80	857.12	<b>Furfuryl alcohol</b>	0.91	1.09
8.13	989.59	6-Methyl-5-hepten-2-one	0.14	–
8.72	642.25	No identified Nist05	0.18	–
8.81	701.95	2-Ethyl-1-hexanol	0.20	–
8.92	711.54	Benzyl alcohol	0.46	0.61
10.21	696.60	<b>Phenethyl alcohol</b>	13.19	14.31

RT: retention time. KI: Kovats index.

**Table 2**

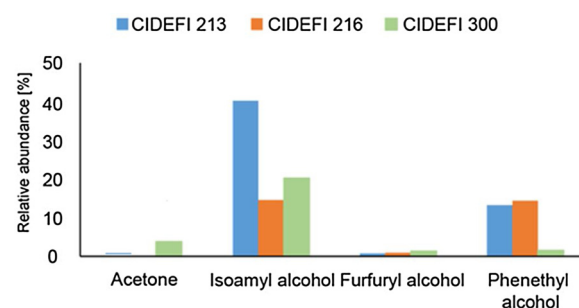
Relative abundance [%] of volatile organic compounds (VOCs) identified by means of a GC–MS analysis in cultures of *F. fulva* CIDEFI 300 strain grown in PDB media. Compounds presented in bold letters also were detected in cultures of *S. lycopersici* strains CIDEFI 213 and CIDEFI 216.

RT (min)	KI	Compound	CIDEFI 300
1.74	629.54	<b>Acetone</b>	<b>3.86</b>
3.59	733.18	Methyl trimethylacetate	8.52
3.73	741.09	3-Methyl-3-buten-1-ol	0.62
3.72	740.64	<b>Isoamyl alcohol</b>	20.13
4.25	770.12	Toluene	0.65
4.64	792.43	1-octene	2.04
5.56	843.83	3-Hexanone, 4-methyl-	1.28
5.80	857.12	<b>Furfuryl alcohol</b>	1.37
5.90	862.78	Ethylbenzene	0.73
6.05	871.19	p-Xylene	0.78
6.13	875.73	4-Heptanone	0.87
6.31	885.65	Bromoform	0.52
6.43	892.60	Styrene	6.77
8.10	988.05	3-Octanone	5.36
9.05	720.15	Hexanoic acid, 2-ethyl-, methyl ester	1.03
9.83	719.66	2-Nonanone	9.34
10.21	696.60	<b>Phenethyl alcohol</b>	1.58
12.67	694.13	No identified Nist05	34.54

RT: retention time. KI: Kovats index.

*F. fulva* strain race OWU harbours 23 gene clusters coding for putative SMs and highlighted that it might be a way that too a large number considering the biotrophic nature of the fungus. These results argue against the hypothesis that biotrophic fungi evolved and developed such a strategy of interaction with plants by losing gene coding for SMs.

We identified organic compounds that are involved in virulence, *quorum-sensing*, differentiation and other processes within fungi that might alter plant-fungal interactions. Isoamyl, phenethyl and furfuryl alcohols as well as acetone were synthesized by cultures of both fungal species (Fig. 1). Isoamyl alcohol was the main common organic compound among the strains, with a relative abundance > 14.6%. Alcohol production has been studied mostly in *Saccharomyces cerevisiae* that synthesizes a wide array of alcohols, among them fusel alcohols that result from the amino acids fermentation [41]. Hazelwood et al. [42] found that when fungi are cultured under nitrogen limiting conditions, frequently they synthesize aromatic compounds such as isoamyl and isobutyl alcohols, that have been associated with the activation of processes related with virulence [33]. Amino acids like valine, leucine, isoleucine, methionine, and phenylalanine are assimilated via the Ehrlich pathway. Interestingly, compounds synthesized through this pathway might trigger *quorum-sensing*, which leads to the induction of differentiation and probably yeast cells adaptation to the environment [41,42]. Leucine, under nitrogen limiting conditions, is the precursor of



**Fig. 1.** Relative abundance [%] of volatile organic compounds (VOCs) identified by means of a GC–MS analysis in cultures of *S. lycopersici* CIDEFI 213 and CIDEFI 216 strains and in cultures of *F. fulva* CIDEFI 300 strain grown in PDB media that were found within the three studied strains.

isoamyl alcohol [43], a compound that provokes cell elongation, pseudohyphal growth and chitin synthesis [42]. In line with this, also germination of fungal spores is stimulated by isoamyl alcohol [44]. Phenethyl alcohol is also synthesized and released by *S. lycopersici* (> 13.19%) and *F. fulva* (1.58%) studied isolates and it might work as a growth controlling compound like in *Candida albicans* [45]. Furfuryl alcohol, another compound synthesized and released by both fungal species, at lower concentrations than 1% is a reduced less reactive derivative of furfural [46]. Under microaerophilic conditions furfural triggers reactive oxygen species (ROS) production, unlike furfuryl alcohol, that provokes a reduction of ROS and therefore cells are not damaged [47], thus suggesting that this type of compounds might play a role in symptom development on tomato leaves.

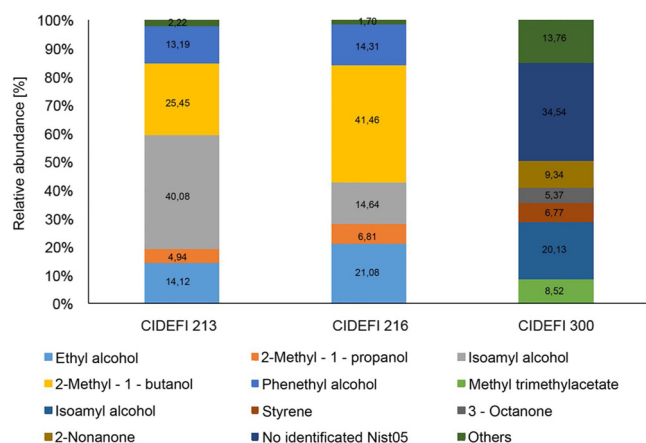
Acetone was another compound detected in cultures of both fungal pathogens but it was produced by only one *S. lycopersici* strain, particularly in CIDEFI 213 culture in a low proportion (0.34%) compared to cultures of *F. fulva* (3.86%). Several authors described the production of acetone–butanol–ethyl alcohol through a fermentation process led by solventogenic *Clostridium* species [48–50].

In summary, when *S. lycopersici* and *F. fulva* are grown under oxygen and/or nitrogen limiting conditions, isoamyl alcohol, phenethyl alcohol, furfuryl alcohol and acetone synthesis is triggered. These VOCs might be turning on transduction signal pathways that incidentally led to mycelial growth autostimulation and/or inhibition of another putative competitor in a particular environment. All these considerations suggest that oxygen and nitrogen might play a key regulatory role in *S. lycopersici* and *F. fulva* volatile compound synthesis.

Both phytopathogens, *S. lycopersici* and *F. fulva*, synthesize SMs like some of them are VOCs that include primarily alcohols, ketones and aldehydes [33] that though they are not essential for fungal growth, they may provide adaptive advantages in nature [51,52]. In addition to this, *S. lycopersici* also has the potential to secrete a broad host range of cell-wall-degrading enzymes and toxins, which is probably related to its necrotrophic capacity [53]. On the contrary, *F. fulva*, a non-obligate biotrophic fungus [11], is thought to be under an evolutionary process of a convergent loss of genes coding for secondary metabolic enzymes, which might occur through the reduction of genes encoding specific toxin transporters. This might additionally reduce the ability of *F. fulva* to secrete enzymes and toxins compared to necrotrophic fungi, which is in line with its ecological behaviour when it interacts with tomato [33].

### 3.2. VOCs synthesized by *Stemphylium lycopersici* CIDEFI 213 and CIDEFI 216 strains

The relative abundance of VOCs released by *S. lycopersici* CIDEFI213 and 216 cultures is presented in Fig. 2. Both isolates synthesized and released 6 compounds Ethyl alcohol, 2-methyl-1-propanol, 2-methyl-1-butanol, 6-methyl-5-hepten-2-one, 2-ethyl-1-hexanol and benzyl alcohol that were not detected in *F. fulva* CIDEFI 300 cultures. These



**Fig. 2.** Relative abundance [%] volatile organic compounds (VOCs) identified by means of a GC-MS analysis in cultures of *S. lycopersici* CIDEFI 213 and CIDEFI 216 strains and in cultures of *F. fulva* CIDEFI 300 strain grown in PDB media. Compounds with relative abundance < 5% were grouped as “Others”.

compounds, together or alone, might be involved in several biological process.

The first one, ethyl alcohol, is the main compound released by several fungi [41]. 2-methyl-1-propanol, has fungivore attractant activity [54]. Recently, Li et al. [55] reported that strains of *Verticillium* also produce 2-methyl-1-propanol and phenylethyl alcohol, though their biological role is unknown [56,57]. In a few dimorphic fungi, including plant pathogens, *quorum-sensing* mechanisms have been identified that might be triggering pathogenic processes. Berrocal et al. [58] suggested that 2-methyl-1-butanol might be mediating *quorum-sensing* dependent mechanisms in fungi of the genus *Ophiostoma*. This compound also has been found in cultures of *Aspergillus niger*, *A. versicolor* and *Penicillium brevicompactum* [59]. Furthermore, Mercier and Jimenez [60] found that *Muscodor albus* synthesizes and releases a mixture of 2-methyl-1-butanol and isobutyric acid, which appears to successfully control postharvest plant diseases. In addition to this, Hung et al. found that 2-methyl-1-butanol, stimulated chlorophyll synthesis in *A. thaliana* plants [57]. In summary, all these findings suggest that 2-methyl-butanol might play a key role in *quorum-sensing* and chlorophyll synthesis in plants that might be critical in the *Stemphylium*-Tomato interaction. The fact that 2-methyl-1-butanol was not detected in cultures of *F. fulva* raises a question regarding either the role of such compounds in *quorum-sensing* during *F. fulva*-Tomato interaction or on *quorum-sensing* itself.

On the other hand, two compounds, 6-methyl-5-hepten-2-one and 2-ethyl-1-hexanol only were released by cultures of *S. lycopersici* CIDEFI 213. The former one induced germination of urediniospores of *Puccinia*

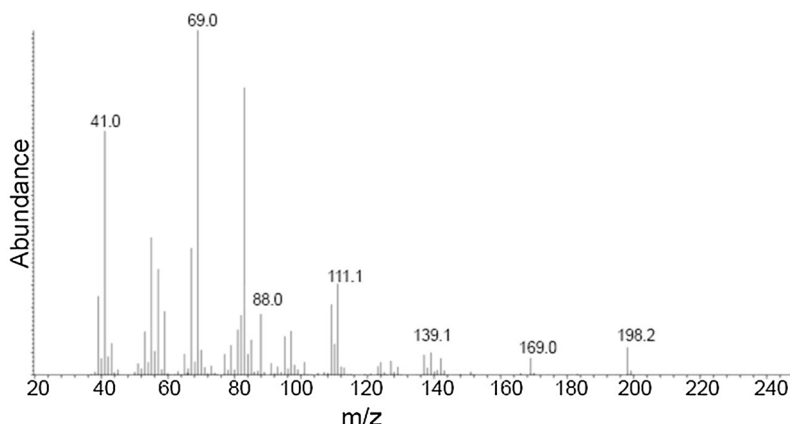
*graminis*, *P. coronata*, *P. sorghi* and *P. recondite* [44] and also has been associated to citral detoxification in *Penicillium expansum* [61,62]. The other one, 2-ethyl-1-hexanol, triggered inhibition of mycelial growth and spore germination [63,64] and also was synthesized and released by isolates of *Pseudomonas* sp., inhibiting *Sclerotinia sclerotiorum* spore germination and growth [65]. Hence, the role of 2-ethyl-1-hexanol deserves further attention regarding its biological role in plant-microbe interactions.

Another VOC found in cultures of *S. lycopersici* was benzyl alcohol, a compound that has antifungal activity [63,66] though the most important difference between *S. lycopersici*, CIDEFI 213 and CIDEFI 216 isolates, were their ability to synthesize isoamyl alcohol and 2-methyl-1-butanol (*sec*-butyl carbinol), particularly the latter one was abundant in cultures of CIDEFI 216, which might be associated with its virulence [6].

These results confirmed that *S. lycopersici* synthesizes a set of SMs with a wide array of biological roles like antagonisms, which might confer *S. lycopersici* a competitive advantage over other organisms. Strikingly, this does not seem to be the case of *F. fulva*, a fungal pathogen that interacts with tomato in a different way that *S. lycopersici*.

### 3.3. VOCs synthesized by *Fulvia fulva* CIDEFI 300 strain

*Fulvia fulva* also synthesizes and release VOCs (Fig. 2). The compound represented the most (34.5%) has a retention time of 1267 min, KI 694.13 and a mass of approximately 198.2 atomic mass unit (Fig. 3), however, we were unable to find a compound with similar characteristics in the NIST05 and Adams libraries. Also, *F. fulva* produced 2-nonanone (9.4%), a compound with antifungal activity [44,63,67], that also is synthesized by bacteria [68,69]. Another VOCs synthesized and released by *F. fulva* were methyl trimethylacetate (8.5%, methyl 2,2-dimethylpropionate) and styrene (6.8%). The former compound might be the precursor of other metabolites such as dimethylpropionate, a compound that protects plants from pathogens by inducing systemic resistance [70]. On the other hand, Furia and Bellanca, Li et al. and Wen et al. found that styrene is indicative of the presence of pathogens in fruits [71–73]. The styrene secreted by *Penicillium expansum* significantly reduced the attraction exerted by pieces of pine twigs upon pine weevil's (*Hylobius abietis*) cut [74]. *F. fulva* also synthesized and released 3-octanone (5.4%), a compound mostly related with mouldy, earthy, mushroom flavours [75]. In addition to this, 3-octanone at low concentration repelled *Megaselia halterata* [76] and at high ones, inhibited fungal growth [77]. The 3-octanone of *Cladosporium* spp. reduced disease symptoms in *A. thaliana* infected with *P. syringae* pv. *tomato* [78] mostly because it induced the systemic resistance of plants to diseases. Furthermore, 3-octanone proved to be phytotoxic on *A. thaliana*, where it triggered an oxidative burst [79,43]. Also, other minor compounds were detected within cultures of *F. fulva*, like 1-



**Fig. 3.** Mass spectra of the more abundant compound detected by headspace GC-MS from cultures of *F. fulva* CIDEFI 300 strain grown on PDB media for 14 days.



octene (2.0%), 3- hexanone, 4 methyl- 3- hexanone (1.3%), hexanoic acid, 2- ethyl-, methyl ester (1.0%), 4- heptanone (0.9%), p- xylene (0.8%), ethylbenzene (0.7%), toluene (0.6%), 3- methyl-3-buten-1-ol (0.6%) and bromoform (0.5%). Although *Cladosporium cladosporioides* produced relatively high concentrations of 1-octene its biological role is unknown [80]. Three- hexanone enhanced growth of *A. thaliana* [69], while 4-methyl- 3- hexanone was found to repel insects [81]. It is well known that plant defensive mechanisms, like SIR and/or SAR contribute to plant health since they conform the plant immune system [82]. Fungal VOCs, like caryophyllene, m-cresol, methyl benzoate, 3-octanone, 1-octen-3-ol, 6-pentyl-a-pyrone activated induced systemic resistance in plants [83]. *F. fulva* synthesizes 3-octanone that based on the findings of Martínez-Medina et al. [84] might play additional roles in plants like activating any of the mechanisms that form the plant immune system.

Our results demonstrated that *F. fulva* synthesizes and secretes antimicrobial compounds against putative competitive microorganisms as well as insects, contributing in this way to its own growth, which possess and environmental advantage for the organism. In accordance with its biotrophic behaviour it seems that the pathogen, secrete compounds that not only stimulate plant growth and health but they also act upon competitors as well as insects.

### 3.4. Study of biological and chemical characteristic of supernatants of fungal cultures

The solubility and vapour pressure at 20 °C of VOCs detected are listed on Additional Table 1. Compounds with high water solubility can be detected by photochemical techniques, whether they and had a biological implication on tomato plants was evidenced by an *in vitro* assay using leaflets.

Regarding the detached leaf assay, both filtered and unfiltered supernatants of *S. lycopersici* provoked the development of a necrotic area quite similar in appearance to grey leaf spot symptoms (Fig. 4 and Additional Fig. 4). Franco et al. [6] described that CIDEFI 216 was more virulent than CIDEFI 213, when the detached leaf assay was carried out using conidia. UV-vis analysis showed that the supernatant of CIDEFI 213 strain has an absorption region between  $\lambda$  240–320 nm with a maximum on  $\lambda$  275 nm. The supernatant of CIDEFI 216 had the same absorption region that CIDEFI 213 but larger amplitude (Fig. 5.A). Apart from these differences on the UV-vis spectra, CIDEFI 213 and CIDEFI 216 strains did not showed differences in fluorescence compared to the control (data not showed). It is possible that the intrinsic fluorescence of the PDB prevent us from seeing the differential fluorescence provoked by compounds secreted by the strains. Furthermore, apparently both *S. lycopersici* strains synthesized similar soluble compounds. Even though CIDEFI 216 secreted more compounds, at least

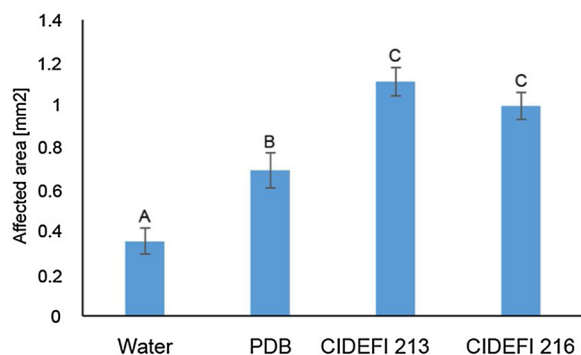


Fig. 4. Average size of the affected area development on detached leaf by filtered supernatant from cultures of *S. lycopersici* grown on PDB media for 7 days. Values are the average of nine replicates. For the same parameter, the mean values followed by different letters are significantly different ( $p < 0.05$ ). Error bars indicates standard deviation.

based on the amplitude of the absorption spectra, most probably not all of them provoked necrosis. In addition to this, both isolates secreted compounds that provoke the death of plant tissue. Hence, the major virulence of isolate CIDEFI 216 described by Franco et al. [6] was most probably due, not only to the presence of low weight metabolites (including VOCs), but also to their interaction with enhancers like VOCs (probably with lower solubility and/or higher vapour pressure) or protein effectors that were synthesized during plant-pathogen interactions.

Last but not least, unfiltered supernatants of *F. fulva* cultures developed typical symptoms of tomato leaf mould on leaves after 7 days of inoculation, which was not observed with filtered supernatants, a response that might be related with the non-obligate biotrophic interaction established between *F. fulva* and Tomato. In addition, UV-vis analysis showed that supernatant of CIDEFI 300 strain has a differential absorption spectra compared to PDB between  $\lambda$  240–280 nm (Fig. 5.B). This change was accompanied with changes in fluorescence emission (Fig. 6). The peak with maximum of fluorescence on  $\lambda_{exc}$  325-  $\lambda_{em}$  420 was more intense in CIDEFI 300 strain. Based on our results, we can infer that the photochemical characteristic of CIDEFI 300 supernatant is a wide array of secreted compounds. In addition, the absence of leaf mould symptoms on detached leaves suggest that these compounds, including identified and unidentified VOCs, do not have the ability to produce disease, at least at the concentration assayed.

## 4. Conclusions

In summary, *S. lycopersici* synthesizes and releases quantitatively more VOCs than *F. fulva*, probably due to the different type of interaction that each fungus establish with Tomato; nevertheless, *F. fulva* synthesized a specific and more diverse spectrum of VOCs.

Production of furfuryl alcohols and derivative compounds by *S. lycopersici* and *F. fulva* may be associated with symptoms development on tomato leaves. In addition, *F. fulva* produces compounds that might contribute to tissue colonization. Since the biological role of the main VOCs released by *F. fulva*, including an unidentified dominant one, remains unknown, future studies should be aimed at elucidating their roles.

This is the first report of the VOCs profiles produced by *S. lycopersici* and *F. fulva*. Hence, this work provides additional information about their ability to synthesize SMs and, thus, (it may shed some light on) the interaction with their hosts.

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## Declaration of Competing Interest

The authors declare that they have no competing interests.

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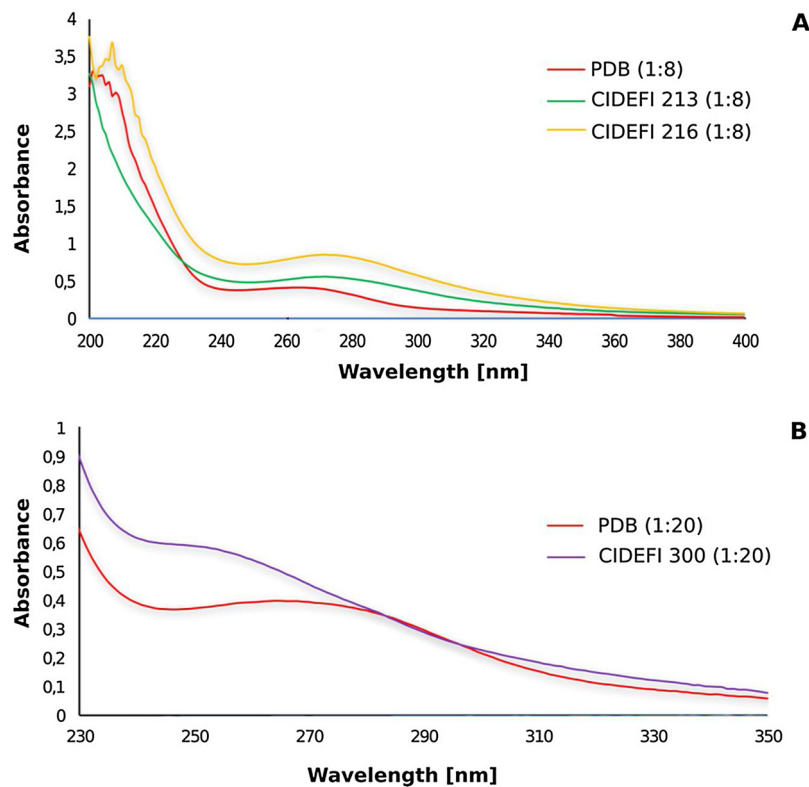


Fig. 5. UV-vis analysis of filtered supernatants of cultures. A. From *S. lycopersici* CIDEFI 213 and CIDEFI 216 strains. B. From *F. fulva* CIDEFI 300 strain.

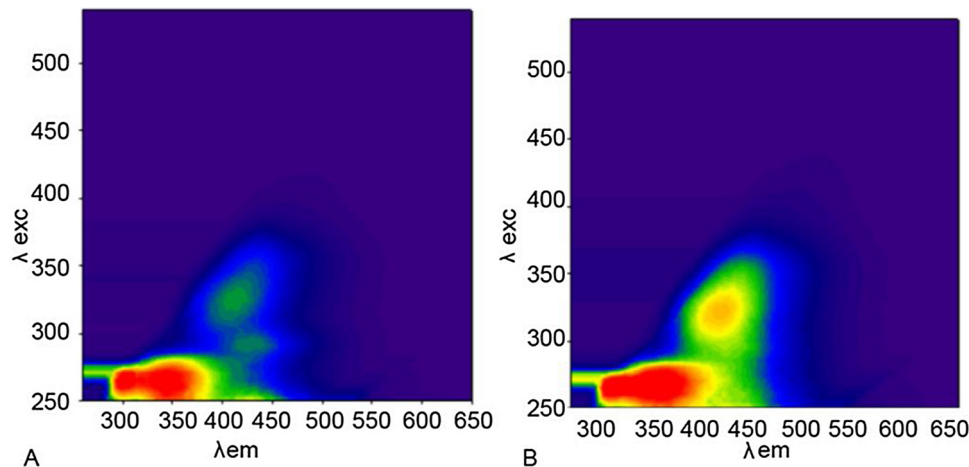


Fig. 6. Fluorescence-excitation-emission matrix (FEEMs). A. Un-inoculated PDB media (1:20). B. *F. fulva* CIDEFI 300 strain (1:20). Graphics were made using the same colour intensity scale.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.cpb.2019.100122>.

## References

- [1] H. Yildizhan, M. Taki, Assessment of tomato production process by cumulative exergy consumption approach in greenhouse and open field conditions: case study of Turkey, *Energy* 156 (2018) 401–408, <https://doi.org/10.1016/j.energy.2018.05.117>.
- [2] FAOSTAT (2016). FAO. <http://faostat.fao.org/>. Accessed 2016.
- [3] R. Medina, S.M.Y. López, M.E.E. Franco, C. Rollan, B.L. Ronco, et al., A survey on occurrence of *Cladosporium fulvum* identifies race 0 and race 2 in tomato-growing areas of Argentina, *Plant Dis.* 99 (2015) 1732–1737, <https://doi.org/10.1094/PDIS-12-14-1270-RE>.
- [4] J.B. Jones, T.A. Zitter, T.M. Mormal, S.A. Miller, *Compendium of Tomato Diseases and Pests*, second ed., American Phytopathological Society, Saint Paul, MN, 2014 ISBN: 978-0-89054-434-1.
- [5] S.I.R. Videira, J.Z. Groenewald, C. Nakashima, U. Braun, R.W. Barreto, et al., *Mycosphaerellaceae*—chaos or clarity? *Stud. Mycol.* 87 (2017) 257–421, <https://doi.org/10.1016/j.simyco.2017.09.003>.
- [6] M.E.E. Franco, M.I. Troncozo, S.M.Y. López, C.G. Lucentini, R. Medina, et al., A survey on tomato leaf grey spot in the two main production areas of Argentina led to the isolation of *Stemphylium lycopersici* representatives which were genetically diverse and differed in their virulence, *Eur. J. Plant Pathol.* 149 (2017) 983–1000, <https://doi.org/10.1007/s10658-017-1248-z>.
- [7] H.H. FLOR, Current status of the gene-for-gene concept, *Annu. Rev. Phytopathol.* 9 (1971) 275–296, <https://doi.org/10.1146/annurev.py.09.090171.001423>.
- [8] P.J.G.M. De Wit, *Cladosporium fulvum* effectors: weapons in the arms race with tomato, *Annu. Rev. Phytopathol.* 54 (2016) 1–23, <https://doi.org/10.1146/annurev-phyto-011516-040249>.
- [9] I. Stergiopoulos, J. Collemare, R. Mehrabi, P.J.G.M. De Wit, Phytotoxic secondary metabolites and peptides produced by plant pathogenic dothideomycete fungi, *FEMS Microbiol. Rev.* 37 (2013) 67–93, <https://doi.org/10.1111/j.1574-6976.2012.00349.x>.

- [10] L. Lo Presti, D. Lanver, G. Schweizer, S. Tanaka, L. Liang, et al., Fungal effectors and plant susceptibility, *Annu. Rev. Plant Biol.* 66 (2015) 513–545, <https://doi.org/10.1146/annurev-arplant-043014-114623>.
- [11] B.P.H.J. Thomma, H.P. Van Esse, P.W. Crous, P.J.G.M. De Wit, *Cladosporium fulvum* (Syn. *Passalora fulva*), a highly specialized plant pathogen as a model for functional studies on plant pathogenic mycosphaerellaceae, *Mol. Plant Pathol.* 6 (2005) 379–393, <https://doi.org/10.1111/j.1364-3703.2005.00292.x>.
- [12] G.S. Gilbert, I.M. Parker, Rapid evolution in a plant-pathogen interaction and the consequences for introduced host species, *Evol. Appl.* 3 (2010) 144–156, <https://doi.org/10.1111/j.1752-4571.2009.00107.x>.
- [13] M.K. Jashni, R. Mehrabi, J. Collemare, C.H. Mesarich, P.J.G.M. De Wit, The battle in the apoplast: further insights into the roles of proteases and their inhibitors in plant–pathogen interactions, *Front. Plant Sci.* 6 (2015) 584, <https://doi.org/10.3389/fpls.2015.00584>.
- [14] D.D. Dhingra, J.B. Sinclair, *Basic Plant Pathology Methods*, second ed., CRC Lewis Publishers, Boca, Florida, 1995 ISBN 978-0-87371-638-3.
- [15] L. Zheng, R. Lv, J. Huang, D. Jiang, Isolation, purification, and biological activity of a phytotoxin produced by *Stemphylium solani*, *Plant Dis.* 94 (2010) 1231–1237, <https://doi.org/10.1094/PDIS-03-10-0183>.
- [16] L. Zheng, R. Lv, Q. Li, T. Liu, J. Huang, et al., Effect of SS-Toxin, a metabolite of *Stemphylium Solani*, on H<sup>+</sup>-ATPase activity and standard redox system in plasma membranes from seedlings leaves of garlic (*Allium Sativum*), *Eur. J. Plant Pathol.* 127 (2010) 419–425, <https://doi.org/10.1007/s10658-010-9608-y>.
- [17] F. Li, F. Xue, X. Yu, GC – MS, FTIR and raman analysis of antioxidant components of red pigments from *Stemphylium lycopersici*, *Curr. Microbiol.* 74 (2017) 532–539, <https://doi.org/10.1007/s00284-017-1220-3>.
- [18] J. Collemare, S. Griffiths, Y. Iida, M.K. Jashni, E. Battaglia, et al., Secondary metabolism and biotrophic lifestyle in the tomato pathogen *Cladosporium fulvum*, *PLoS One* 9 (2014) e85877, <https://doi.org/10.1371/journal.pone.0085877>.
- [19] H.P. Van Esse, J.W. Van't Klooster, M.D. Bolton, K.A. Yadeta, P. Van Baaren, et al., The *Cladosporium fulvum* virulence protein Avr2 inhibits host proteases required for basal defense, *Plant Cell* 20 (2008) 1948–1963, <https://doi.org/10.1105/tpc.108.059394>.
- [20] H.P. Van Esse, M.D. Bolton, I. Stergiopoulos, P.J.G.M. De Wit, B.P.H.J. Thomma, The chitin-binding *Cladosporium fulvum* effector protein Avr4 is a virulence factor, *Mol. Plant Microbe Interact.* 20 (2007) 1092–1101, <https://doi.org/10.1094/MPMI-20-9-1092>.
- [21] N. Westerink, B.F. Brandwagt, P.J.G.M. De Wit, M.H.A.J. Joosten, *Cladosporium fulvum* circumvents the second functional resistance gene homologue at the Cf-4 Locus (Hcr9-4E) by secretion of a stable Avr4E isoform, *Mol. Microbiol.* 54 (2004) 533–545, <https://doi.org/10.1111/j.1365-2958.2004.04288.x>.
- [22] C.H. Mesarich, S.A. Griffiths, A. Van Der Burgt, B. Ökmen, H.G. Beenen, et al., Transcriptome sequencing uncovers the *avr5* avirulence gene of the tomato leaf mold pathogen *Cladosporium fulvum*, *Mol. Plant Microbe Interact.* 27 (2014) 846–857, <https://doi.org/10.1094/MPMI-02-14-0050-R>.
- [23] R. Luderer, M.J.F. De Kock, R.H.L. Dees, P.J.G.M. De Wit, M.H.A.J. Joosten, Functional analysis of cysteine residues of ect elicitor proteins of the fungal tomato pathogen *Cladosporium fulvum*, *Mol. Plant Pathol.* 3 (2002) 91–95, <https://doi.org/10.1046/j.1464-6722.2001.00095.x>.
- [24] S.A. Griffiths, C.H. Mesarich, B. Saccomanno, A. Vaisberg, P.J.G.M. De Wit, et al., Elucidation of cladofulvin biosynthesis reveals a cytochrome P450 monooxygenase required for anthraquinone dimerization, *PNAS* 113 (2016) 6851–6856, <https://doi.org/10.1073/pnas.1603528113>.
- [25] S.A. Griffiths, R.J. Cox, E.J.R. Overdijk, C.H. Mesarich, B. Saccomanno, et al., Assignment of a dubious gene cluster to melanin biosynthesis in the tomato fungal pathogen *Cladosporium fulvum*, *PLoS One* 13 (2018) 1–18, <https://doi.org/10.1371/journal.pone.0209600>.
- [26] R. Medina, C.G. Lucentini, M.E.E. Franco, G. Petroselli, J.A. Rosso, et al., Identification of an intermediate for 1, 8- Melanin synthesis in a race-2 isolate of *Fulvia fulva* (Syn. *Cladosporium fulvum*), *Heliyon* 4 (2018) e01036, <https://doi.org/10.1016/j.heliyon.2018.e01036> 1–21.
- [27] N.P. Keller, Fungal secondary metabolism: regulation, function and drug discovery, *Nat. Rev. Microbiol.* 17 (2018) 167–180, <https://doi.org/10.1038/s41579-018-0121-1>.
- [28] N.P. Keller, G. Turner, J.W. Bennett, Fungal secondary metabolism from biochemistry to genomics, *Nat. Rev. Microbiol.* 3 (2005) 937–947, <https://doi.org/10.1038/nrmicro1286>.
- [29] O. Tyc, C. Song, J.S. Dickschat, M. Vos, P. Garbeva, the ecological role of volatile and soluble secondary metabolites produced by soil bacteria, *Trends Microbiol.* 25 (2017) 280–292, <https://doi.org/10.1016/j.tim.2016.12.002>.
- [30] J.K. Holopainen, J. Gershenzon, Multiple stress factors and the emission of plant VOCs, *Trends Plant Sci.* 15 (2010) 176–184, <https://doi.org/10.1016/j.tplants.2010.01.006>.
- [31] M.E. Maffei, Sites of synthesis, biochemistry and functional role of plant volatiles, *S. Afr. J. Bot.* 76 (2010) 612–631, <https://doi.org/10.1016/j.sajb.2010.03.003>.
- [32] G.I. Arimura, C. Kost, W. Boland, Herbivore-induced, indirect plant defences, *Biochim. Biophys. Acta, Mol. Cell Biol. Lipids.* 1734 (2005) 91–111, <https://doi.org/10.1016/j.bbalip.2005.03.001>.
- [33] T. Pusztahelyi, I.J. Holb, I. Pócsi, Secondary metabolites in fungus–plant interactions, *Front. Plant Sci.* 6 (2015) 1–23, <https://doi.org/10.3389/fpls.2015.00573>.
- [34] T. Lortzing, A. Steppuhn, Jasmonate signalling in plants shapes plant – insect interaction ecology, *Curr. Opin. Insect Sci.* 14 (2016) 32–39, <https://doi.org/10.1016/j.cois.2016.01.002>.
- [35] A. Cellini, G. Burianni, L. Rocchi, S. Savioli, et al., Biological relevance of volatile organic compounds emitted during the pathogenic interactions between apple plants and *Erwinia amylovora*, *Mol. Plant Pathol.* 19 (2018) 158–168, <https://doi.org/10.1111/mpp.12509>.
- [36] R. Medina, P.M. David Gara, A.J. Fernández-González, J.A. Rosso, M.T. Del Panno, Remediation of a soil chronically contaminated with hydrocarbons through persulfate oxidation and bioremediation, *Sci. Total Environ.* 618 (2018) 518–530, <https://doi.org/10.1016/j.scitotenv.2017.10.326>.
- [37] L. Lamari, Assess: Image Analysis Software for Plant Disease Quantification, APS press, 2002.
- [38] J.A. Di Rienzo, F. Casanoves, M.G. Balzarini, L. Gonzalez, M. Tablada, et al., *InfoStat versión 2015*, Universidad Nacional de Córdoba, Córdoba, 2015.
- [39] Á. Trigos, G. Mendoza, C. Espinoza, A. Salinas, J.J. Fernández, et al., The role of macrosporin in necrotic spots, *Phytochem. Lett.* 4 (2011) 122–125, <https://doi.org/10.1016/j.phytol.2010.12.007>.
- [40] S.A. Griffiths, A. Saccomanno, P.J.G.M. De Wit, J. Collemare, Regulation of secondary metabolite production in the fungal tomato pathogen *Cladosporium fulvum*, *Fungal Genet. Biol.* 84 (2015) 52–61, <https://doi.org/10.1016/j.fgb.2015.09.009>.
- [41] M.C. Lorenz, N.S. Cutler, J. Heitman, Characterization of alcohol-induced filamentous growth in *Saccharomyces cerevisiae*, *Mol. Biol. Cell* 11 (2000) 183–199, <https://doi.org/10.1091/mbc.11.1.183>.
- [42] L.A. Hazelwood, J.M. Daran, A.J.A. Van Maris, J.T. Pronk, J.R. Dickinson, The Ehrlich pathway for fusel alcohol production: a century of research on *Saccharomyces cerevisiae* metabolism, *Appl. Environ. Microbiol.* 74 (2008) 2259–2266, <https://doi.org/10.1128/AEM.02625-07>.
- [43] M. Jones, J.S. Pierce, Absorption of amino acids from wort by yeasts, *J. Inst. Brew.* 70 (1964) 307–315.
- [44] R.C. French, The bioregulatory action of flavor compounds on fungal spores and other propagules, *Annu. Rev. Phytopathol.* 23 (1985) 173–199, <https://doi.org/10.1146/annurev.py.23.090185.001133>.
- [45] B.T. Lingappa, M. Prasad, Y. Lingappa, D.F. Hunt, K. Biemann, Phenethyl alcohol and tryptophol: autoantibiotics produced by the fungus *Candida albicans*, *Science* 163 (1969) 192–194, <https://doi.org/10.1126/science.163.3863.192>.
- [46] J.R. Almeida, M. Bertilsson, M.F. Gorwa-Grauslund, S. Gorsich, G. Lidén, Metabolic effects of furanols and impacts on biotechnological processes, *Appl. Microbiol. Biotechnol.* 82 (2009) 625, <https://doi.org/10.1007/s00253-009-1875-1>.
- [47] S. Gorsich, P. Slininger, J. McCaffery, M. Baltmr, The fermentation inhibitor furfural causes cellular damage to *Saccharomyces cerevisiae*, *Biotechnol. Fuels and Chemicals Symposium Proceedings* (2006) 4–16.
- [48] D.T. Jones, D.R. Woods, Acetone-butanol fermentation revisited, *Microbiol. Rev.* 50 (1986) 484–524.
- [49] B. Schiel-Bengelsdorf, J. Montoya, S. Linder, P. Dürre, Butanol fermentation, *Environ. Technol.* 34 (2013) 1691–1710, <https://doi.org/10.1080/09593330.2013.827746>.
- [50] F. Xin, W. Dong, Y. Jiang, J. Ma, W. Zhang, et al., Recent advances on conversion and co-production of acetone-butanol-ethanol into high value-added bioproducts, *Crit. Rev. Biotechnol.* 38 (2018) 529–540, <https://doi.org/10.1080/07388551.2017.1376309>.
- [51] E. Perez-Nadales, M.F.A. Nogueira, C. Baldin, S. Castanheira, M. El Ghalid, et al., Fungal model systems and the elucidation of pathogenicity determinants, *Fungal Genet. Biol.* 70 (2014) 42–67, <https://doi.org/10.1016/j.fgb.2014.06.011>.
- [52] D.H. Scharf, T. Heinekamp, A.A. Brakhage, Human and plant fungal pathogens: the role of secondary metabolites, *PLoS Pathog.* 10 (2014) 10–12, <https://doi.org/10.1371/journal.ppat.1003859>.
- [53] M.E.E. Franco, *Mancha gris de la hoja del tomate: identificación, biología y genómica del agente etiológico*, Doctoral dissertation Facultad de Ciencias Naturales y Museo, 2019.
- [54] S.U. Morath, R. Hung, J.W. Bennett, Fungal volatile organic compounds: a review with emphasis on their biotechnological potential, *Fungal Biol. Rev.* 26 (2012) 73–83, <https://doi.org/10.1016/j.fbr.2012.07.001>.
- [55] N. Li, W. Wang, V. Bitas, K. Subbarao, X. Liu, et al., Volatile compounds emitted by diverse *Verticillium* species enhance plant growth by manipulating auxin signalling, *Mol. Plant Microbe Interact.* 31 (2018) 1021–1031, <https://doi.org/10.1094/MPMI-11-17-0263-R>.
- [56] H.A. Naznin, M. Kimura, M. Miyazawa, M. Hyakumachi, Analysis of volatile organic compounds emitted by plant growth-promoting fungus *Phoma* sp. GS8-3 for growth promotion effects on tobacco, *Microbes Environ.* 28 (2013) 42–49, <https://doi.org/10.1264/jsme2.ME12085>.
- [57] R. Hung, S. Lee, C. Rodríguez-Saona, J.W. Bennett, Common gas phase molecules from fungi affect seed germination and plant health in *Arabidopsis thaliana*, *AMB Express* 4 (2014) 1–7, <https://doi.org/10.1186/s13568-014-0053-8>.
- [58] A. Berrocal, J. Navarrete, C. Oviedo, K.W. Nickerson, Quorum sensing activity in *Ophiostoma ulmi*: effects of fusel oils and branched chain amino acids on yeast–mycelial dimorphism, *J. Appl. Microbiol.* 113 (2012) 126–134, <https://doi.org/10.1111/j.1365-2672.2012.05317.x>.
- [59] S. Moularat, E. Robine, O. Ramalho, M.A. Oturan, Detection of fungal development in closed spaces through the determination of specific chemical targets, *Chemosphere* 72 (2008) 224–232, <https://doi.org/10.1016/j.chemosphere.2008.01.057>.
- [60] J. Mercier, J.I. Jiménez, Control of fungal decay of apples and peaches by the biofumigant fungus *Muscodor albus*, *Postharvest Biol. Technol.* 31 (2003) 1–8, <https://doi.org/10.1016/j.postharvbio.2003.08.004>.
- [61] L. Siroli, F. Patrignani, F. Gardini, R. Lanciotti, Effects of sub-lethal concentrations of thyme and oregano essential oils, carvacrol, thymol, citral and trans-2-hexenal on membrane fatty acid composition and volatile molecule profile of *Listeria monocytogenes*, *Escherichia coli* and *Salmonella enteritidis*, *Food Chem.* 182 (2015) 185–192, <https://doi.org/10.1016/j.foodchem.2015.02.136>.
- [62] Y. Wang, K. Feng, H. Yang, Y. Yuan, T. Yue, Antifungal mechanism of cinnamaldehyde and citral combination against: *Penicillium expansum* based on FT-IR

- fingerprint, plasma membrane, oxidative stress and volatile profile, RSC Adv. 8 (2018) 5806–5815, <https://doi.org/10.1039/C7RA12191A>.
- [63] S.F. Vaughn, G.F. Spencer, B.S. Shasha, Volatile compounds from raspberry and strawberry fruit inhibit postharvest decay fungi, J. Food Sci. 58 (1993) 793–796, <https://doi.org/10.1111/j.1365-2621.1993.tb09360.x>.
- [64] L. Weisskopf, The potential of bacterial volatiles for crop protection against phytopathogenic fungi, in: A. Méndez- Vilas (Ed.), Microbial Pathogens and Strategies for Combating Them: Science, Technology and Education, second edition, 2013, pp. 1352–1363.
- [65] W.D. Fernando, R. Ramarathnam, A.S. Krishnamoorthy, S.C. Savchuk, Identification and use of potential bacterial organic antifungal volatiles in biocontrol, Soil Biol. Biochem. 37 (2005) 955–964, <https://doi.org/10.1016/j.soilbio.2004.10.021>.
- [66] S.M. Al-Reza, A. Rahman, Y. Ahmed, S.C. Kang, Inhibition of plant pathogens *in vitro* and *in vivo* with essential oil and organic extracts of *Cestrum nocturnum* L., Pesticide Biochem. Physiol. 96 (2010) 86–92, <https://doi.org/10.1016/j.pestbp.2009.09.005>.
- [67] J. Song, R. Leepipattanawit, W. Deng, R.M. Beaudry, Hexanal vapor is a natural, metabolizable fungicide: inhibition of fungal activity and enhancement of aroma biosynthesis in apple slices, J. Am. Soc. Hortic. Sci. 121 (1996) 937–942.
- [68] R.A. Andersen, T.R. Hamilton-Kemp, D.F. Hildebrand, C.T. McCracken Jr, R.W. Collins, et al., Structure-antifungal activity relationships among volatile C6 and C9 aliphatic aldehydes, ketones, and alcohols, J. Agric. Food Chem. 42 (1994) 1563–1568.
- [69] U. Groenhagen, R. Baumgartner, A. Bailly, A. Gardiner, L. Ebert, et al., Production of bioactive volatiles by different *Burkholderia ambifaria* strains, J. Chem. Ecol. 39 (2013) 892–906, <https://doi.org/10.1007/s10886-013-0315-y>.
- [70] C.J. Huang, J.F. Tsay, S.Y. Chang, H.P. Yang, W.S. Wu, et al., Dimethyl disulfide is an induced systemic resistance elicitor produced by *Bacillus cereus* C1L, Pest Manage. Sci. 68 (2012) 1306–1310, <https://doi.org/10.1002/ps.3301>.
- [71] T.E. Furia, N. Bellanca, second ed., Fenaroli's Handbook of Flavor Ingredients Vol. 2 CRC Press, Francis & Taylor, Cleveland, OH, 1975 ISBN 0-87819-533-5.
- [72] C. Li, G.W. Krewer, P. Ji, H. Scherm, S.J. Kays, Gas sensor array for blueberry fruit disease detection and classification, Postharvest Biol. Technol. 55 (2010) 144–149, <https://doi.org/10.1016/j.postharvbio.2009.11.004>.
- [73] Y.Q. Wen, F. He, B.Q. Zhu, Y.B. Lan, Q.H. Pan, et al., Free and glycosidically bound aroma compounds in cherry (*Prunus Avium* L.), Food Chem. 152 (2014) 29–36, <https://doi.org/10.1016/j.foodchem.2013.11.092>.
- [74] M. Azeem, G.K. Rajarao, H. Nordenhem, G. Nordlander, A.K. Borg-Karlson, *Penicillium expansum* volatiles reduce pine weevil attraction to host plants, J. Chem. Ecol. 39 (2013) 120–128, <https://doi.org/10.1007/s10886-012-0232-5>.
- [75] C. Schueuermann, C.C. Steel, J.W. Blackman, A.C. Clark, L.J. Schwarz, et al., A GC–MS untargted metabolomics approach for the classification of chemical differences in grape juices based on fungal pathogen, Food Chem. 270 (2019) 375–384, <https://doi.org/10.1016/j.foodchem.2018.07.057>.
- [76] R.M. Pfeil, R.O. Mumma, Bioassay for evaluating attraction of the phorid fly, *Megaselia halterata* to compost colonized by the commercial mushroom, *Agaricus bisporus* and to 1-octen-3-ol and 3-octanone, Entomol. Exp. Appl. 69 (1993) 137–144, <https://doi.org/10.1111/j.1570-7458.1993.tb01736.x>.
- [77] Y.J. Cardoza, H.T. Alborn, J.H. Tumlinson, *In vivo* volatile emissions from peanut plants induced by simultaneous fungal infection and insect damage, J. Chem. Ecol. 28 (2002) 161–174, <https://doi.org/10.1023/A:1013523104853>.
- [78] H.A. Naznin, D. Kiyohara, M. Kimura, M. Miyazawa, M. Shimizu, et al., Systemic resistance induced by volatile organic compounds emitted by plant growth-promoting fungi in *Arabidopsis thaliana*, PLoS One 9 (2014) e86882, , <https://doi.org/10.1371/journal.pone.0086882>.
- [79] R. Spilvallo, M. Novero, C.M. Berteau, S. Bossi, P. Bonfante, Truffle volatiles inhibit growth and induce an oxidative burst in *Arabidopsis thaliana*, New Phytol. 175 (2007) 417–424, <https://doi.org/10.1111/j.1469-8137.2007.02141.x>.
- [80] F.X. Prenafeta-boldú, N. Roca, C. Villatoro, L. Vera, G.S. De Hoog, Prospective application of melanized fungi for the biofiltration of indoor air in closed bioregenerative systems, J. Hazard. Mat. 361 (2019) 1–9, <https://doi.org/10.1016/j.jhazmat.2018.08.059>.
- [81] D.M. Norris, Insect attractants and repellents, Handbook of Natural Pesticides, CRC Press (Taylor & Francis Group), Boca Raton, FL 33487-2742, 2018, pp. 135–149.
- [82] C.N. Kanchiswamy, M. Malnoy, M.E. Maffei, Bioprospecting bacterial and fungal volatiles for sustainable agriculture, Trends Plant Sci. 20 (2015) 206–211, <https://doi.org/10.1016/j.tplants.2015.01.004>.
- [83] N. Li, A. Alfiky, M.M. Vaughan, S. Kang, Stop and smell the fungi: fungal volatile metabolites are overlooked signals involved in fungal interaction with plants, Fungal Biol. Rev. 30 (2016) 134–144, <https://doi.org/10.1016/j.fbr.2016.06.004>.
- [84] A. Martínez-Medina, S.C. Van Wees, C.M. Pieterse, Airborne signals from *Trichoderma* fungi stimulate iron uptake responses in roots resulting in priming of jasmonic acid dependent defences in shoots of *Arabidopsis thaliana* and *Solanum lycopersicum*, Plant Cell Environ. 40 (2017) 2691–2705, <https://doi.org/10.1111/pce.13016>.